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(Commemoration Issue Dedicated to
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New Experimental Approaches to the Detection of Solar Neutrinos

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The cosmological implications of the low result of the famous Davis experiment on ^{37}Cl to measure the flux on earth of the high energy component of the solar neutrino emission is discussed. It is now considered imperative to determine whether the reason lies in some defect of the standard solar model or in our understanding of the relevant nuclear physics of the postulated hydrogenburning fusion reactions in the solar core or of the physics of electron neutrinos. Such determination depends on a difficult measurement of the flux of the low energy component of the solar neutrino emission, that produced by the primary proton-proton fusion. Four proposed experiments designed to measure that flux, using targets of ^7Li , ^{71}Ga , ^{115}In , and ^{205}Tl are described and compared.

KEY WORDS Solar fusion reactions/ Solar neutrinos/ Solar models/ ^{37}Cl detector of high energy neutrinos/ Detectors for proton fusion neutrinos, ^7Li , ^{71}Ga , ^{115}In , ^{205}Tl /

I. INTRODUCTION

One of the most astonishing, stimulating and fruitful developments in the ever growing interactions among the sciences is that of astrophysics. The list of advances and discoveries of the last forty years, well within the active professional career of Professor Shimizu, that have drastically and profoundly altered our views of the cosmos, -its origins, its ongoing processes, its great variety-, includes most of the recent flowering of physics on earth in counterpart to a whole zoo of new celestial objects and processes. One can juxtapose new physics with new astronomy in so many mutually interacting ways: general relativity with black holes; gravitational waves, neutral current neutrino interactions and synchrotron radiation with supernovae and their nebulae; isotope formation with r, s, p, alpha and fission processes in stellar cores; plasma physics with stellar structure; particle physics with cosmic rays; 3°K microwaves and the big bang; asymmetry in the 3°K relict radiation and new galactic kinematics; microwaves and x-rays with radio and x-ray stars; relativity and the closed (?), open (?), but expanding universe; solid state physics, magnetohydrodynamics, degenerate matter physics and superconductivity with neutron stars and pulsars; perhaps yet more exotic physics with quasars; and nuclear physics and the processes of energy generation in stars.

In even peripheral contact with this vast development one gains the sense of a

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broad yet penetrating and brilliant intellectual enterprise whose growth is assembling this entire domain into an internally coherent construct. Much of this edifice rests, however, on the foundation of a few fundamental observations and measurements and on the concepts they support.

II. THE SOLAR NEUTRINO PROBLEM

Of course, in this brief time span one expects gaps in the assembled picture. One such very serious gap is the dilemma posed by the well known solar neutrino problem,¹⁾ whose resolution is fundamental to most current astrophysical modeling of stellar evolution, of nucleosynthesis, of supernovae, of pulsar and neutron star formation, of the big bang and of course to understanding stellar energy production. Even our concept of a stable solar emission of heat and light, with the solar surface gradually increasing in brightness (15% in 4×10^9 years) according to the predictions of the standard solar model, is suspect in the light of accumulating evidence.²⁾ It appears that the solar interaction with earth climatology must differ considerably from present models in both its short-term and long-term behavior, which implies deep solar convection and circulation, contrary to the standard solar models, that can result in gross changes in solar interior energy production. The only available key to experimental exploration of these deep solar core processes, with their cosmic and earthly implications, is the measurement of the *flux* on earth and the *energy spectrum* of the neutrinos emitted in the postulated hydrogen-burning sequence of nuclear fusion reactions within the sun, and, if possible, the study of their long term temporal variation.

The problem exists because the accumulated results of the beautiful and justly acclaimed experiment of Raymond Davis, Jr. of Brookhaven National Laboratory in the United States indicate that the intensity of the very weak high energy component of the solar neutrino flux on earth is only 1.6 ± 0.4 solar neutrino units (SNU) whereas the prediction of the standard solar model calculations for his experiment is 4.7 ± 1 SNU, three times greater. (1 SNU = 10^{-36} neutrino captures per second per target atom). In this experiment, neutrinos of minimum energy 0.82 MeV are captured by ^{37}Cl nuclei in a target of 615 tons of C_2Cl_4 to produce about ten atoms of 35 day ^{37}Ar per month. The ^{37}Ar is periodically isolated by bubbling helium through the liquid and its electron-capture decay to ^{37}Cl is counted to assay the neutrino captures. Data has been accumulated over the past ten years.

The fairly complex series of fusion reactions presumed to take place deep in the solar core (and in all main sequence stars), and the detailed assumptions underlying the standard solar model, are described in all modern astronomy textbooks. The principal assumptions are: initially homogeneous composition as observed in solar spectra; hydrostatic equilibrium between gas-plus-radiation pressure and gravitational compression; and semi rigid body rotation. The energy production chain initiates with the thermal fusion of two protons, (p-p reaction) at the core temperature of 15,000,000°K, to produce, by the weak interaction, a deuteron, a positron and a neutrino of continuous low energy distribution with $E_{\text{max}} = 0.42$ MeV. Several branchings in the fusion lead to the production, with widely varying yields, of five more higher energy neutrino emitting decays. These neutrino groups are listed in table I with their emitting parents or reactions, their

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Table I. Neutrino Fluxes on Earth of Standard Solar Model

Source or reaction	Energy of neutrino (MeV)	Flux ($\times 10^{-10} \text{ cm}^{-2} \text{ sec}^{-1}$)
1) p-p	0-0.42	6.1
2) p-e-p	1.44	0.015
3) ${}^7\text{Be}$	0.86	0.3
4) ${}^{13}\text{N}$	0-1.2	0.03
5) ${}^{15}\text{O}$	0-1.7	0.02
6) ${}^8\text{B}$	0-14	0.0003

energies and their fluxes on earth as given by the standard solar model. The net result of the fusion reactions is the conversion of hydrogen to ${}^4\text{He}$ (hydrogen burning) with the release of 26.4 MeV per ${}^4\text{He}$, in four parallel fusion chains. This energy ultimately (after 1.9 million years of energy transfer by radiative diffusion) is radiated from the solar surface as black body thermal radiation at the surface temperature of 6,000°K; the neutrinos presumably emerge immediately, unhindered, carrying a few percent of the energy released, and even at the earth constitute a flux of $6 \times 10^{10} \text{ sec}^{-1} \text{ cm}^{-2}$, of which 95% is the primary p-p neutrino flux.

Because of the 0.82 MeV energy threshold of ${}^{37}\text{Cl}$, only the upper 5% of the composite neutrino energy spectrum can be captured. Moreover, the existence in ${}^{37}\text{Ar}$ of the isobaric analogue of the ${}^{37}\text{Cl}$ ground state, at 5.2 MeV, enables the very high energy (0-14 MeV) but very low intensity neutrinos from the ${}^8\text{B}$ group (only) to be captured via this state, with such greatly increased probability that these constitute about 75% of all neutrino captures. Thus ${}^{37}\text{Cl}$ is essentially a monitor on the ${}^8\text{B}$ neutrinos, and the low result of the Davis experiment can be interpreted (among many other ways) as a deficiency in this neutrino group, whose flux is only 1/20,000 of the total neutrino flux. This special sensitivity to the ${}^8\text{B}$ flux was a principal reason for choosing the ${}^{37}\text{Cl}$ reaction, because the production rate of ${}^8\text{B}$ is an extremely steep function of solar core temperature, *ca.* T^{13} , so its neutrino flux measurement makes ${}^{37}\text{Cl}$ a solar core thermometer. But the temperature reduction implied by the low result of the ${}^{37}\text{Cl}$ experiment implies inconsistency with the standard solar model calculations.

III. ALTERNATIVE INTERPRETATIONS

A great variety of radical revisions of currently accepted aspects of the solar model or of the relevant nuclear or neutrino physics have been proposed,¹⁾ aimed at drastically lowering the predicted neutrino capture rate in ${}^{37}\text{Cl}$. Although these are extensively discussed, none has gained experimental support or even modest acceptance. The experimentally accessible physics of the nuclear fusion reactions involved and of the spectroscopic atomic oscillator strengths determining solar plasma opacities and hence radiative energy transport and core temperatures have been extensively refined, yielding even firmer confirmation of the input data of the standard solar model.

Most of the non-standard models are addressed to sharp reduction of the tiny ${}^8\text{B}$ neutrino flux, thus attaining near agreement with the Davis value. They achieve the

necessary core temperature lowering by various changes in initial model assumptions or ad-hoc auxiliary solar processes that alter the computed behavior of the solar model, such as: lower heavy element concentration in the core; continuous or periodic core-mantle convective mixing, caused by rapid core rotation, strong internal magnetic fields, periodic plasma instability, *etc.*; partial energy transport by acoustic waves; non-Maxwellian tails on energy distributions, *etc.* Even central black holes or intermediate vector bosons, ^3He burning, variation of gravitational or other fundamental constants with time or with solar radial position, and decay or oscillation of neutrinos have been invoked. (The last would give 1/3 detectable neutrinos.) But at the present stage there is no serious consideration of other sources than fusion for the 4.7 billion year solar power output.

Although the Davis result gives great latitude for the exercise of fertile scientific imagination, certain basic facts sharply constrain the results of solar model building, such as the solar mass, radius, surface temperature and composition, and importantly, its age and luminosity. With these alone, coupled with the assumptions of quasi-equilibrium between surface luminosity and central energy production rate, and of hydrogen burning as the long term energy source, any model (except the pure CNO catalytic cycle model, already ruled out by the ^{37}Cl data) will yield a neutrino production rate from the p-p fusion reaction within several percent of that of the standard solar model, *i.e.*, this flux is largely insensitive to the model details or to the core temperature.

IV. PROPOSED EXPERIMENTS

Since the low Davis result does not confirm (or strongly deny) the basic hypothesis of solar hydrogen burning, there is now universal agreement¹⁾ among astro-, nuclear and neutrino physicists and chemists that the goal must now shift to that of establishing whether this is indeed the solar energy source, *i. e.*, one must design the more difficult detection of p-p neutrinos. If in newly designed experiments the flux of the abundant, primary, low energy p-p neutrino component is found to be about $6 \times 10^{10} \text{ sec}^{-1} \text{ cm}^{-2}$, this will affirm that the neutrinos emitted in hydrogen burning reach earth unchanged and will suggest, from the ^{37}Cl result, that one of the low ^8B -production solar models applies, but the new experimental results cannot in themselves hope to achieve the accuracy required to distinguish among the standard or many variant models of hydrogen burning. If a low value is observed, say about 1/3 of the prediction, in agreement with ^{37}Cl , one must look to neutrino oscillations³⁾ as possible cause; or the solar fusion rate may now be suppressed by a transient core cooling episode, of theoretical duration $1-2 \times 10^6$ years, due to core-mantle convective mixing following a plasma instability build-up. Such a low or even lower result will also force consideration of the drastic consequences to current astrophysics of this lack of confirmation of hydrogen burning, for alternatives to solar neutrino spectroscopy to explore the solar core are difficult to conceive.

Several experiments to detect p-p neutrinos have been proposed¹⁾ and are being actively developed. The four most promising methods using neutrino capture targets of ^7Li , ^{71}Ga , ^{115}In , and ^{205}Tl will be described, and their merits and demerits compared. There is real advantage in having the broadest possible scientific audience informed about these extraordinarily difficult experiments during their formative stages with the possibility of beneficial interaction and feedback of ideas.

Detection of Solar Neutrinos

All proposals for detecting low energy solar neutrinos involve their capture in a target nucleus with the ejection of an electron in a reaction inverse to the decay of the product nucleus back to the target by the capture of a bound (or free) electron, with the emission of a neutrino. The neutrino capture probability is thus proportional to the inverse reduced electron capture decay probability which is measured by its reciprocal ft value. This value must be determined with sufficient precision to enable a neutrino flux measurement to make the fairly gross discriminations among alternative interpretations, *e.g.*, hydrogen burning or neutrino oscillations or transiently reduced fusion rate.

The extraordinarily small cross sections for interactions of such low energy neutrinos, expressed in units of 10^{-46}cm^2 , enforces the use of either very large targets (it is conventional to speak of the tons of each target material needed to give one standard-solar-model neutrino capture per day) or of very long capture times (millions of years). Thus these experiments can practically realize only modest accuracy although sufficient to the achievement of their very important goals; note that the ^{37}Cl measurement attained a statistical accuracy of 25% in ten years.

Each of these detectors, except ^{115}In , involves the detection of an ultramicro mass of a radioactive product accumulated during an irradiation period in the isobaric target. Thus each encounters the requirement for the chemical isolation of tracer concentrations of product atoms from massive targets, necessitating the development of chemical purifications of unprecedented decontamination factors, *e.g.*, 10^{-28} for the ^{71}Ge product of neutrino capture in ^{71}Ga . The methods share in common the need for efficient detection, *i.e.*, counting, of the few atoms produced, and also the difficult problems of minimizing, and accounting for, the residual contributions of many alternative nuclear "background" reactions that can produce the same isotopic product, or masking background signals in the detector.

^7Li . The ^7Li experiment is being explored by Dr. J. K. Rowley, a Brookhaven colleague of Raymond Davis. This detector forms 53 day ^7Be from neutrino capture in ^7Li (92.3%) in natural lithium. The ^7Be decay has the very favorably low value of $\log ft=3.3$, giving a predicted value of 27.3 SNU for the standard solar model, corresponding to a target mass for one neutrino capture per day of only 5 tons of natural lithium, at modest cost of \$100,000.

However, the energy threshold for neutrino capture is 0.862 MeV, even higher than for ^{37}Cl , so p-p neutrinos cannot be captured. Its current consideration is based on the prediction of the standard solar model that about 1/3 of the capture rate in lithium is due to the 1.44 MeV "p-e-p" neutrinos; these are produced by the alternative channel to proton fusion by a three body weak electron capture interaction with a theoretical relative rate, under solar core conditions, of 1/400 the p-p rate. The large sensitivity to other components of the neutrino spectrum, and the theoretical uncertainty in the estimated p-e-p/p-p fluxes make ^7Li a less attractive detector.

The chemical separation method being developed is based on a liquid-liquid extraction of beryllium from an acidic aqueous solution of 12 M LiCl in 0.0005 M HCl using 0.01 M dibutylphosphoric acid in kerosene as extractant. The phases are mixed by circulating pump for several hours, and after the phases separate the Be is back extracted from the kerosene into 2 M HCl. On a 2000 liter scale, 1% of the full experi-

ment, 97% extraction efficiency of 100 μgm of Be carrier is obtained, which satisfies the experimental needs. There are chemical problems, however, with the removal of tracer contaminations of alpha emitters in the radium and lead isotopes. By a series of (α, n) , (n, p) and then ${}^7\text{Li}(p, n){}^7\text{Be}$ reactions in the LiCl target a significant background is produced, requiring scrupulous removal of the α emitters.

Cosmic ray muons of multi-GeV energies also penetrate the target, producing protons by electromagnetic interaction; these in turn, after slowing down, give the (p, n) reaction that gives the same product as neutrino capture in all target isotopes. This source of background is a major concern, if not the dominant interference, in all radiochemical neutrino detectors. The cross-sections for these muon-induced reactions have been studied for the ${}^7\text{Li}$, ${}^{37}\text{Cl}$ and ${}^{71}\text{Ga}$ targets in the Fermilab muon beam by the Brookhaven group and for ${}^{205}\text{Tl}$ by the Argonne group. For ${}^7\text{Li}$ the result indicates a 10% contribution of muon-induced background to the solar neutrino capture rate, but there are some uncertainties remaining. For each of the target experiments except ${}^{205}\text{Tl}$ the solution to this problem is to place the target far enough underground to sufficiently attenuate the muon flux; for the ${}^{37}\text{Cl}$ experiment the target is 1.46 km deep in a mine.

The major difficulty of the ${}^7\text{Li}$ experiment is the efficient detection of the ${}^7\text{Be}$ product. Whereas in the decay of ${}^{37}\text{Ar}$ by K electron capture 2.6 keV is released in the form of Auger electrons, enabling detection of the decay by placing the ${}^{37}\text{Ar}$ into a small proportional counter, ${}^7\text{Be}$ electron capture gives only a 0.05 keV Auger electron, too weak to be able to discriminate against counter background. Only a 10% branch decays to a 477 keV level whose gamma ray can be counted, but this method would require a tenfold increase in Li target mass to retain one *countable* neutrino capture per day. Other methods of detecting the ${}^7\text{Be}$ product are being considered, such as mass spectrometry, laser two-step ionization of the ${}^7\text{Li}$ daughter of ${}^7\text{Be}$ decay and counting the ionized electron, *etc.* Such detection of a very few atoms with very high efficiency is required to maintain the cost and target mass advantages of the ${}^7\text{Li}$ detector. As noted, it is also marginal in terms of not being clearly a proton fusion detector.

${}^{71}\text{Ga}$. The ${}^{71}\text{Ga}$ experiment, also developed by Raymond Davis's Brookhaven group, is in the most advanced state of preparation of all the proposals. The 11.8 day ${}^{71}\text{Ge}$ product of neutrino capture decays by electron capture with a Q_{ec} value of 236 keV (compared to $E_{\text{max}}=420$ keV for p-p neutrinos) and a well measured $\log ft=4.3$. From this the standard solar model neutrino capture rate predictions give 92 SNU of which 65 result from p-p neutrinos and 21 from ${}^7\text{Be}$ neutrinos. In illustration of the insensitivity of the p-p flux and of the response of essentially p-p neutrino detectors to the details of the hydrogen burning solar models, the prediction of the extreme "p-p and pep only" model for ${}^{71}\text{Ga}$ is 71 SNU (67.5 SNU from p-p), and for the "maximal convective mixing" model, 82 SNU (67.5 SNU from p-p).

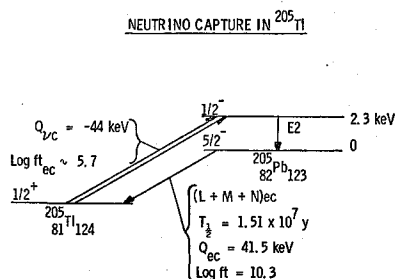
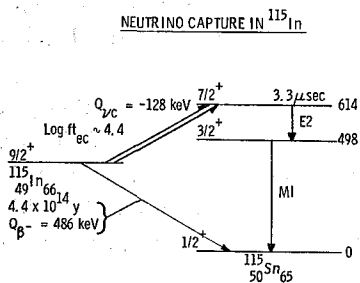
A one-neutrino-capture-per-day detector gives a saturation number of ~ 17 atoms of ${}^{71}\text{Ge}$. Such a detector requires ~ 50 tons of natural gallium, at a cost of 15-25 million dollars. Current world annual production of gallium is about 20 tons, extracted from bauxite in aluminum electrodeposition as a by product, and used mostly in solid state devices such as light emitting diodes. Obtaining 50 tons for several years use in the experiment will be difficult.

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Very effective chemical separations have been developed for the extraction of 1 mg of carrier Ge from either Ga metal, or from GaCl_3 in aqueous solution, on a 20 kg scale. The metal is the more available form, and is liquid at 20°C . Ge can be leached in a few minutes from Ga metal which has been rendered into a fine emulsion in weak acid by agitation, using an acidified H_2O_2 leach. The emulsion spontaneously breaks down into two phases within minutes in more concentrated HCl , with the GeCl_4 in the acid, with 90% recovery of micro concentrations of Ge. (From GaCl_3 the volatile GeCl_4 can be swept out with helium bubbles.) After volume reduction the Ge (and As impurity) are reduced to hydrides with sodium borohydride (NaBH_4) in alkaline solution, and the GeH_4 and AsH_3 can be extracted and mutually separated by gas chromatography due to their volatility. No difficulties are anticipated in scaling up to the 50 ton scale. The decay of the ^{71}Ge can be counted in the same very small low background anti-coincidence shielded proportional counters that are used to count ^{37}Ar , with somewhat lower counting efficiency for the ^{71}Ge ; this will require improvement.

The background produced by $^{71}\text{Ga}(p, n)^{71}\text{Ge}$ reactions will be minimized by placing the large 8 m^3 target tanks in the deep mine next to the ^{37}Cl experiment to attenuate the cosmic ray muon flux; by shielding the tank with some meters of water to moderate fast neutrons from (α, n) and fission from the surrounding rock walls (the fast neutrons make (n, p) reactions in the tank); and by purifying the gallium from α emitters which make (α, p) reactions. Natural Ga provides a self monitor in the $^{69}\text{Ga}(p, n)^{69}\text{Ge}$, $T_{1/2}=39$ hours, reaction, for the residual proton flux. Alpha reactions on Ga produce ^{72}As (26 h) and ^{74}As (18 d) which are very effective monitors on the residual alpha particle flux; the As activities can be separated, as above, and counted, to give background determinations. From the cross sections measured in the aforementioned Fermilab muon beam experiments, the ^{71}Ge production rate in the one-neutrino capture-per-day Ga target in the mine due to muons is estimated as 0.012 atoms/day. To reduce the ^{71}Ge production by α induced reactions to 0.1 atoms/day, thorium (in equilibrium) must be less than 0.7 gm in the gallium or tank walls, and ^{226}Ra must be less than $0.05\text{ }\mu\text{gm}$. The Brookhaven group believe these limits can be achieved, and the monitoring reactions will indicate the contributions of these backgrounds. The yield of the $^{68}\text{Zn}(\alpha, n)^{71}\text{Ge}$ reaction on Zn impurity is deemed negligible.

^{115}In . The proposal to use ^{115}In as an on-line instantaneous counting detector for p-p neutrinos and the development of the remarkable and innovative techniques is the work of R. S. Raghavan and his colleagues of Bell Laboratories. Neutrinos of minimum energy



128 keV capture in ^{115}In (95.7%, $T_{1/2}(\beta^-) = 4.4 \times 10^{14} \text{ y}$) populating the second excited state in ^{115}Sn at 614 keV, and ejecting an electron with kinetic energy $E_e = E_\nu - 128$ (Fig. 1). This 3.3 μsec metastable state decays through a cascade of 116 keV–498 keV gamma rays to the ^{115}Sn ground state. The experiment consists of detecting this characteristic triple coincidence signal signature of each neutrino capture event, with energy, spatial correlation, and timing selection on each of the signals, the electron, the delayed 116 keV gamma and the promptly following 498 keV gamma. As Raghavan notes,⁴⁾ this scheme is analogous to that of the classic experiment to detect the antineutrino of Reines *et al.*⁵⁾

Three different detection schemes, used alone or in combination, are being investigated. In each the massive indium target-detector combination is effectively divided into many small cells ($\sim 400,000$) to achieve the correlation sequence: the electron and the delayed 116 keV gamma detected as full energy peaks in the same small volume, sufficiently large to ensure their efficient detection but not that of the 498 keV gamma, whose detection as a full energy peak in one of the near or second nearest layers of surrounding cells is required. In the method described in^{1,4)} the indium is dissolved in a liquid scintillator which is contained in a closepacked array of long tubes, about 5 cm diam \times 1 m long, viewed at each end by a photomultiplier. The ratio of paired photomultiplier signals can locate the scintillation to 10 cm. 40,000 such tubes would contain the 3.7 tons of indium calculated to be a one standard-solar-model neutrino-capture-per-day target. The photomultipliers would be connected via computer logic to select the desired coincidences. Such an array is estimated to have a detection efficiency for the triple coincidence, with the required energy, spatial and timing correlations, of *ca.* 50%, so the target mass and circuitry need doubling for one detected neutrino per day. The developers believe they can devise light guide arrays that may reduce the required number of photomultipliers to as few as 5000, which would be a major economy. Even this number with associated circuitry will cost *ca.* \$5,000,000. Another scintillation detector method being examined involves stacked plastic scintillator planes sandwiched with mylar tapes plated with indium. A third method uses multiwire high pressure proportional drift chamber counters to localize the signals, either alone or in conjunction with the other detectors, with the indium disposed in thin grids.

The ^{115}In detector has the important advantage over other methods that the electron signal in the triple coincidence measures the energy of the neutrino, so this is a true neutrino spectrometer. The standard solar model prediction (see below) for the capture rate is 534 SNU for p-p neutrinos and 99 SNU for ^7Be neutrinos and a total of 660 SNU; thus the ^7Be nearly monoenergetic neutrino component can be distinguished and the p-p neutrino spectrum measured above 128 keV, in principle, which would furnish convincing evidence of their solar origin, and combined with the ^{37}Cl data would resolve three of the six solar neutrino groups.

On the other hand, the resolution of the desired signal from the background signals is a formidable task, though the proponents believe it possible. The ^{115}In decays by 4th forbidden β^- transition to the ^{115}Sn ground state with $E_{\text{max}} = 486 \text{ keV}$, and a one-capture-per-day target gives 10^6 such betas *per second*, for a desired-signal/noise ratio of 10^{-11} from this source alone, and a huge signal rate into the electronics. It is the random coincidence rate from these betas, with the energy windows passing segments of the beta

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continuum, either three such beta signals or two such in random coincidence with an externally produced gamma-or cosmic ray-standin for the 498 keV γ that can simulate a neutrino capture event. The published calculations⁴⁾ show the latter chance events to be the most difficult to suppress, requiring extra active (anti-coincidence) and passive shielding; the former can in principle be reduced to 0.01 chance events per day, by the full set of requirements on the signals.

The ^{115}In (and also the ^{205}Tl) neutrino absorption cross section calculations must be based on estimated or indirectly measured inverse electron capture rates of the product level, since in these two cases the product excited state decays by electron capture with so unmeasurably small a branching ratio relative to its decay by gamma ray or internal conversion, 10^{-12} for ^{115}Sn and 10^{-17} for ^{205}Pb . For the former the $\log ft$ value (4.4) is estimated⁴⁾ by a small extrapolation from the sequence of known analogous beta decays connecting the same $g_{9/2}$ proton- $g_{7/2}$ neutron shell model states in the odd mass 113, 117, 119, 121 In-Sn isotope pairs, although Bahcall^{1,6)} has discussed reservations concerning the error estimate⁴⁾ of 10% for ft : 30% disagreements with⁴⁾ appear in Bahcall's calculations. Raghavan proposed the measurement of the neutrino absorption cross section directly on the solar neutrino detector with an intense neutrino source of ^{51}Cr , but I believe this will be quite impractical with attainable source strengths. This uncertainty in the neutrino cross section can perhaps be reduced with data from (p, n) and nucleon transfer experiments comparing ^{71}Ga , ^{87}Rb , and ^{115}In reactions to the final neutrino-capture states.⁶⁾

It is apparent that this will be a very expensive experiment, of the order at least of \$10,000,000.

^{205}Tl . Solar neutrino capture in ^{205}Tl to produce ^{205}Pb ($T_{1/2}=15$ million years) was proposed and is being developed by the author and colleagues at Argonne National Laboratory.^{1,7)} Neutrino capture occurs almost exclusively to the 2.3 keV $1/2^-$ level in ^{205}Pb , which decays promptly to the ground state. The threshold is 44 keV making this the most predominantly p-p neutrino detector, 85%, with 12% due to ^7Be neutrinos.

Five features distinguishing this proposal from the others all follow from the long decay lifetime of the product isotope. First, the measurement is made on the accumulated ^{205}Pb concentration built up over past times of the order of the half life in crystalline thallium minerals that have retained the ^{205}Pb product trapped in the lattice, *i.e.*, that have integrated and averaged the solar neutrino reactions over periods of the past millions of years. Thus the derived neutrino flux is an average over the lifetime of the mineral, or of the order of the mean life of ^{205}Pb , whichever is less. Now, if the parameters of the real sun differ from those of the standard model such that the core plasma develops instabilities leading to aperiodic transient episodes of core-mantle mixing with resultant core cooling and reduction of the fusion and hence neutrino emission rates, as has been advocated,^{1,8)} and should the sun now be in such a transient phase, this might account for the low ^{37}Cl result, and would yield similar low results for any of the above three detectors, which all examine the existing flux. Since, however, such calculated instabilities are predicted to endure 1-2 million years, the neutrino flux averaged over much longer times must be equal to that of similar models *without such instabilities* if only hydrogen burning be the sole energy source. Thus the ^{205}Tl detector will

give the full expected p-p flux value if the neutrinos all reach earth in a detectable form, whichever model applies, or *e.g.*, 1/3 the full value if neutrinos oscillate among three types, whereas the other p-p neutrino detectors cannot distinguish the transient mixing model from *e.g.*, neutrino oscillations or decay. Should ^{205}Tl give the full result, then with the results of *e.g.*, the ^{71}Ga detector, the question of steady-state vs. transiently-unstable behavior can be resolved.

Secondly, the long integration time builds up enormously higher concentrations of product atoms in the target, *e.g.*, *ca.* 50 atoms of ^{205}Pb per gm of thallium mineral compared to 17 atoms of ^{71}Ge in 50 tons of gallium. Thus it appears possible to make a measurement with a few kg. of thallium mineral, from which *ca.* 10^5 atoms of ^{205}Pb are assayed with small statistical error, compared to *ca.* 100 detected events per year of counting that is the prospect of the other experiments.

In contrast to these virtues one has three disadvantages associated with the long life of the product: firstly, one cannot count the atoms by the efficient observation of their radioactive decay, but must develop other usually less efficient techniques which must be able to discriminate against the residual isobaric target atoms that may contaminate the chemically separated product atoms; also, the chemical separation must achieve exceptionally high decontamination of target atoms.

Secondly, one cannot control the experimental conditions of the neutrino irradiation, *e.g.*, by interposing large masses of rock and water shielding against background generating radiations like cosmic ray muons and neutrons, nor purify the target and its surroundings; one must impose limiting requirements on these conditions and then accept the best sample that one can find in nature.

Thirdly, since one does not control the irradiation time, and if it is not very long compared to the 15 million year ^{205}Pb half life, it is necessary to measure the age of the mineral with reasonable precision. A variety of standard methods are being considered, with the not unreasonable goal of 5-10% accuracy.

The measurement would use 10 kg of the Tl mineral lorandite, TlAsS_2 , the only available and suitable crystalline form, found in adequate abundance and purity only in a deposit in Yugoslavia, at a depth of 120 m, and of estimated age 10-15 million years. After separation of the mineral from the enclosing ore matrix and division into four samples, the coarse chemical separation of Pb would, as presently planned, be followed by final stages which alternate 3-4 cycles of liquid-liquid chromatographic columns with anion exchange columns, each attaining a Tl decontamination factor of 3-4 orders of magnitude, for an overall reduction of Tl by 10^{-20} . A stage of isotope enrichment of mass 205 by 10^4 in the Argonne electromagnetic isotope separator is interposed before the final chemistry stages. Each final sample would contain *ca.* 2×10^4 atoms of ^{205}Pb , 2×10^{14} atoms of ^{206}Pb remaining from the *ca.* 2 ppm of natural lead impurity in the lorandite, and either *ca.* 10^5 atoms of ^{205}Tl or many orders of magnitude more, depending on the final choice of a method of assay for the ^{205}Pb .

If mass spectrometry is chosen, ^{205}Pb cannot possibly be resolved from ^{205}Tl , so the Tl tolerance in the sample is necessarily small (only *ca.* $10 \times \text{Pb}$), the separation based only on the different volatilities of the two species in the surface ionization source, for the ^{205}Tl to contribute negligibly during the ion-by-ion counting of the ^{205}Pb mass peak. With attained Pb ionization efficiencies in our ion source, *ca.* 500 ions will be counted

per sample, giving statistical uncertainties of a few percent, and overall assay errors of order 10–15%. Our 100'' mass spectrometer can tolerate a $^{206}\text{Pb}/^{205}\text{Pb}$ ratio of 10^{11} .

If we succeed in the development of an alternate assay method its Tl tolerance will be higher by many orders of magnitude, thus simplifying the chemistry. It is based on the use of laser resonance excitation and polarization with polarized laser beam of ^{205}Pb atoms in the gas phase, with the detection of the excited atoms of each Pb isotope separately by NMR scanning of the sample whose polarization is being measured with a second linearly polarized laser beam. With this method there is prospect for single atom ^{205}Pb sensitivity, very high residual ^{205}Tl tolerance, and even higher tolerance for other Pb isotopes in the sample than in the mass spectrometer, thus perhaps avoiding the need for the isotope enrichment stage in the separation of ^{205}Pb , which loses 90% of the sample.

The neutrino capture to the excited state in ^{205}Pb faces the same difficulty indicated for ^{115}In , that the ft value for the inverse decay cannot be measured directly due to the overwhelming competition, $\times 10^{17}$, of the 2.3 keV E2 transition to the ground state. In this case the problem of evaluating the neutrino capture cross section is more difficult than for ^{115}In , because, although there are several well-measured neighboring beta transitions similarly connecting well defined shell model states, $s_{7/2}$ proton with $p_{7/2}$ neutron states, and with $\log ft$ values near 5.3, to which analogy can be made, the wave function of $^{205}\text{Tl}^{1/2+}$ ground state has the appropriate component that connects to the $^{205}\text{Pb}^{1/2-}$, 2.3 keV state by a single particle weak interaction transition as only a minor component of uncertain amplitude. Theoretical calculations and experimental measurements of the amplitude of this wave function component based on nucleon transfer reactions among Pb and Tl isotopes give fairly consistent values from which we calculate the neutrino absorption cross sections and then SNU value, giving $183 \text{ SNU} \pm 40\%$, corresponding to 56 ± 23 atoms per gm of 10,000,000 year old lorandite.

This uncertainty in the prediction is too large to justify a neutrino flux measurement with this detector, for the result could not unambiguously discriminate among the alternatives of current interest that were indicated at the beginning of section IV. If the uncertainty can be reduced to 20%, these discriminations can be made fairly cleanly. We are engaged in a variety of experiments: nucleon transfer to the interesting corresponding states in ^{205}Tl and ^{205}Pb and in analogue pairs such as ^{207}Tl – ^{207}Pb , ^{209}Tl – ^{209}Pb and ^{205}Hg – ^{205}Tl that have well measured analogue beta transitions; measurement of the radiative width of the 19.3 MeV electric dipole gamma decay of the isobaric analogue state of ^{205}Tl in ^{205}Pb to the 2.3 keV, $1/2^-$ state, as the electromagnetic analogue of the weak neutrino-capture reaction in ^{205}Tl , to determine major nuclear matrix elements that govern both transition rates in common. There is hope that with these and similar measurements and further theoretical calculations that the existing 40% predictive uncertainty in the SNU value can be halved, to make the neutrino flux measurement meaningful.

Problems of background ^{205}Pb formed by up to 34 competing nuclear reactions on Tl, Pb and other impurities in the mineral *in situ* by a variety of natural radiations are significant compared to the expected neutrino capture yield in only two cases; $^{204}\text{Pb}(n, \gamma)$ ^{205}Pb , with the neutrons coming primarily from (α, n) reactions produced on certain light isotopes by the high energy, low intensity Th C' alphas from Th impurities in rock surrounding the ore, estimated to yield 2–8% of the solar neutrino capture rate; and the

$^{205}\text{Tl}(p, n)^{205}\text{Pb}$ reactions induced by cosmic ray muons. The existing rock shielding over the Yugoslavian ore deposit is only 120 m, which is insufficient. However, preliminary studies of the amount of overburden rock that has been removed by erosion show it to be about 200-300 m within at most the last million years, a time short compared to the ten million year estimated age of the lorandite. Thus the rock shielding was 300-400 m over most of the last half life of ^{205}Pb ; this value will be more accurately known with geological studies at the ore site. With this shielding, and with the results of our measurements of the $^{205}\text{Tl}(p, n)^{205}\text{Pb}$ excitation function, the contribution of muon induced background will be 10-20% of the neutrino capture rate, depending mostly on the final neutrino capture cross section values.

If the experiment can be done, its cost will be less than \$1,000,000.

V. SUMMARY

All solar neutrino flux measurements are difficult; on the other hand, the information they may yield is of universally recognized importance. Ideally they should all be done, to supplement each other in the detailed information each gives. At this time, the ^{71}Ga experiment seems most feasible, the principal problems being the availability of gallium and the high cost. The spectroscopic information provided by the ^{115}In measurement is uniquely useful in its ability to assign solar origin to the neutrinos and to distinguish the p-p and ^7Be neutrino components, but it faces a long development period, extreme background noise and electronic problems and also large cost. The ^{205}Tl experiment give unique information on long time neutrino flux average, with the ability to distinguish fluctuating neutrino emission from neutrino physics effects that may account for the ^{37}Cl result, and it is relatively inexpensive, but it faces a difficult problem in refining the accuracy of the neutrino cross section value, and the major development of technique is in the future. The ^7Li experiment is also inexpensive, but the detection problem is not solved and the interpretation of results is not free of ambiguities in terms of hydrogen burning. These do not exhaust the possibilities for attacking this problem; one needs only interest, perseverance, and the help and ideas of one's colleagues everywhere.

VI. EPILOGUE

It is a great pleasure to dedicate this preview to Professor Sakae Shimizu. I know from personal observation that he shares with me the abiding conviction that a life of research in science conveys the deepest and most enduring of satisfactions. As long as problems of such fascination and far reaching importance as the solar neutrino puzzle exist, and clearly this will be so for long into the future, the challenge and lure of participation keeps one young. May this be so for many years to come for our respected colleague, teacher and friend, Sakae Shimizu.

REFERENCES

- (1) Proceedings of Informal Conference on Status and Future of Solar Neutrino Research. 2 Vols. Jan. 5-7, 1978. Ed. G. Friedlander Brookhaven National Laboratory report BNL-

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50879.

- (2) John A. Eddy, *Science*, **192**, 1189 (1976) Eugene Parker ; private communication.
- (3) V. Gribov and B. Pontecorvo, *Phys. Lett.*, **28B**, 495 (1969).
- (4) R. S. Raghavan, *Phys. Rev. Letters*, **37**, 259 (1976) ; L. Pfeiffer, A. P. Mills, Jr., R. S. Raghavan, and E. A. Chandross, *Phys. Rev. Letters*, **41**, 63 (1978).
- (5) F. Reines, C. L. Cowan, F. B. Harrison, H. W. Kruse, and A. D. McGuire, *Phys. Rev.*, **117**, 159 (1960).
- (6) John N. Bahcall, *Rev. Mod. Phys.*, to be published.
- (7) M. S. Freedman, C. M. Stevens, E. P. Horwitz, L. H. Fuchs, J. L. Lerner, L. S. Goodman, W. J. Childs, and J. Hessler, *Science*, **193**, 1117 (1976)
- (8) F. W. W. Dilke and D. O. Gough, *Nature*, **240**, 180 (1972).
Roger K. Ulrich, *Science*, **190**, 619 (1975)
A. G. W. Cameron, *Rev. Geophysics and Space Physics*, **11**, 2, 505 (1972).